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The researchers proposed to develop and test a framework for designing and analyzing complex control systems consisting of independent modules, called agents, that communicate through fixed channels. These agents possess and acquire knowledge, and negotiate with one another regarding the use of their capabilities. The results were along the following dimensions: real-time, machine, and environments; agent-oriented programming; temporal data bases; anytime belief update; planning and control; social rules, utilities and organizations.

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## Summary of results from Air-Force-sponsored research on Intelligent Real-Time Problem Solving

by

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in collaboration with Tom Dean

(then visiting Stanford, now back at Brown University)

We proposed to develop and test a framework for designing and analyzing complex control systems consisting of independent modules, called agents, that communicate through fixed channels. These agents possess and acquire knowledge, and negotiate with one another regarding the use of their capabilities.

Briefly, our architecture associates an 'agent' with each low-level sensor and effector, and in addition considers 'supervisory agents' whose job it is to pool the information from the various sensors and deploy them sensibly. This coordination is implemented by issuing commands and requests to the various other agents. These commands and requests take into account the capabilities of each agent, where capabilities include the temporal information (e.g., "the sonar is capable of delivering a reading at frame rate"). More specifically, the capabilities of each agent specify the accuracy of the information it is capable of delivering as a function of the time available, and the efficient coordination

of agents in time-critical situations will depend on the ability to make time/precision tradeoffs, in the spirit of "anytime" approximation algorithms.

In conjunction with exploration of this architecture we hoped to produce precise technical results that others in the community would be able to build upon. Here is a summary of our results that are the most relevant to IRTPS.

**Real time, machines and environments.** In the IRTPS kickoff meeting, two separate groups proposed that a precise formulation of real-time properties such as responsiveness, reactivity and sensitivity to environmental changes required a framework in which to express the coupling of machines and environments. As part of our research we have developed such a framework, called *temporal automata*. It contains careful mathematical development of the ideas, as well as a practical simulator in which we have encoded a number of devices. It should be commented that there are a number of related activities in the areas of specification and verification, of which the IRTPS community would be well advised to take note; currently *timed IO automata* appear to be the hottest item.

Relevant publications:

@techreport(LavignonShohamTR, author="J.-F. Lavignon and Y. Shoham", title="Temporal Automata", Institution=Stanford University, Computer Science Department, number="STAN-CS-90-1325", year=1990)

@techreport(LavignonTR, author="J.-F. Lavignon", title="A Simulator for Temporal Automata", Institution=Stanford University, Computer Science Department, year=1990)

**Agent Oriented Programming** Our approach relied on a framework for integrating the activity of several local agents. We have developed the general framework of Agent Oriented Programming (AOP), including its theoretical underpinning as well as its practical implementation. For the latter we designed a family of real-time agent interpreters, and implemented a simple instance of those called Agent-0.

Relevant publications:

@inproceedings(LinShohamProvably, author="F. Lin and Y. Shoham", title="Provably Correct Theories of Action (preliminary report)", booktitle=Proc. NCAI, address=Anaheim, CA, year=1991)

@misc(LinShohamPersistence, author="F. Lin and Y. Shoham", title="On the persistence of knowledge and ignorance", howpublished=to be submitted, year=1992)

@misc(LinShohamConcurrent, author="F. Lin and Y. Shoham", title="Concurrent Actions in the Situation Calculus", howpublished=submitted, year=1991)

### Temporal data bases

Knowledge-based real-time systems require, among other things, the ability to efficiently represent and compute which properties hold at different times. A mechanism that has gained popularity in recent years is the so-called *time-map manager* (this mechanism is closely related to the event calculus). As we have multiple agents which must encode the beliefs of other agents (e.g., the supervisor records the beliefs of both the camera agent and the sonar agent), we have generalized the concept of time maps. *Temporal belief maps* are essentially an extension of the one-dimensional time maps to higher dimension; the rules of persistence in high dimensions are somewhat more subtle than in one dimension.

#### Relevant publications:

@inproceedings(IsozakiShohamFGCS, author="H. Isozaki and Y. Shoham", title="A mechanism for Reasoning about Time and Belief", booktitle=Submitted to FGCS92, address=Tokyo, Japan, year=1991)

@inproceedings(IsozakiShohamTBmaps, author="H. Isozaki and Y. Shoham", title="Temporal Belief Maps", booktitle=to be submitted, year=1992)

### Anytime belief update

Another major requirement in real-time systems is the updating of beliefs and plans based on newly acquired information. This requires determining what constitutes correct update, and designing methods for achieving this efficiently. For the former, we have recently managed to analytically derive commonsense rule of update from a basic theory of action. For the latter, although it is easy to show that in general the problem of update is intractable, there is a procedure that promises to be reasonably behaved in many cases (we have formulated the procedure, proved its correctness and complexity, but have not yet tested it on substantial cases). Furthermore, this procedure has an "anytime" flavor, in the sense that it can be interrupted during execution and provide the update of the database, given the new information processed thus far.

#### Relevant publications:

@misc(ShohamdelValActionUpdate, author=Y. Shoham and A. del Val, title=Database Update and Theories of Action, howpublished=to be submitted, year=1991)

@misc(DelValShohamAlgorithms, author=Y. Shoham and A. del Val, title=Algorithms for Revision and Update, howpublished=manuscript, year=1991)

### Planning and control

We realized some time ago that the integration of reasoning and sensory-motor activity, a noticable strand in the IRTPS effort, required looking carefully at the connection with control theory. Motivated and funded partially by IRTPS, Dean spent time studying the topic, culminating with the book coauthored by Wellman.

Relevant publication:

@book(DeanandWellman91, author = Dean, Thomas and Wellman, Michael, title = Planning and Control, publisher = Morgan Kaufmann, address = San Mateo, California, year = 1991)

### Social rules, utilities and organizations

Using the agent-based system, we have performed some preliminary experiments in the application areas of modular control systems for mobile robotics and distributed agents for transportation scheduling. The preliminary experiments show clearly that without additional structure, programming such systems to perform useful work is quite difficult. This has led us to investigate a number of related disciplines, such as economics and organizational theory.

We first considered constraints of several kinds to facilitate coordination among agents. The one has been the design of social laws, which on the one hand allow restrict the behavior of each agent so that conflicts are minimized or completely avoided, and on the other hand still allow agents to achieve their goals without consuming too many resources (such as time or energy). We have formulated a general theory, called *constrained automata*, and have investigated the role of social law in one real-time application, navigation of multiple robots.

We also noted that without the availability of common global utility measure, programming such systems to perform useful work is quite difficult. It should be noted that having the same measure of utility does not imply having the same expectation of utility since different agents will in general have different knowledge of the state of the entire system. Under the assumption of all agents possessed of the same global utility measure, it is easy to build truly distributed controllers for relatively simple problems whose overall performance degrades gracefully in the presence of escalating communication failure.

In our early experiments, we noticed that the algorithms we were writing for distributed agents looked a lot like the sort of voting schemes used for routing in communication networks. Each agent gathers information about the state of other agents that it believes can either help or hinder the tasks that it is assigned. It then engages in negotiations with those agents regarding what actions each agent is considering. These negotiations take the form of voting on possible outcomes resulting from actions. Given that all agents possess the same utility function, if the agents have difficulty reaching consensus, the only reason could be that they possess different expectations over outcomes. Negotiation proceeds by agents building local interest groups based on the potential for interaction, trying to reach consensus on collective actions, and then iterating as time allows to take into account more knowledge when available.

Finally, we were led to investigate the utility of the notions of *structured organizations* and *teams*, all of whose members have the same basic objectives. It is our expectation that we can make direct use of some of the basic methods suggested in economics and organizational theory for real-time applications by augmenting the criteria used by agents in voting to account for expectations regarding (i) the gains to be had from additional communication and negotiation, and (ii) the losses due to opportunities lost by delaying action. We are just beginning to experiment along these lines and hope to have some results in the near future.

Relevant publications:

@misc(ShohamTennenholtzGrid, author=Y. Shoham and M. Tennenholtz, title=On Traffic Laws for Mobile Robots, howpublished=Submitted, year=1991)

@misc(ShohamTennenholtzConstraint, author=Y. Shoham and M. Tennenholtz, title=Constrained Automata, howpublished=in preparation, year=1992)